

Prospects for a Quantum Dynamic Random Access Memory (Q-DRAM)

S. Bandyopadhyay*

Department of Electrical Engineering
University of Nebraska
Lincoln, Nebraska 68588-0511, USA

Abstract

Compared to quantum logic gates, quantum memory has received far less attention. Here, we explore the prognosis for a solid-state, scalable quantum dynamic random access memory (Q-DRAM), where the qubits are encoded by the spin orientations of single quantons in exchange-decoupled quantum dots. We address, in particular, various possibilities for implementing refresh cycles.

*Corresponding author. E-mail: bandy@quantum1.unl.edu

1 Introduction

Quantum memory is an important constituent of quantum information science. It has many applications: (i) increasing the efficiency of quantum key distribution (QKD) protocols (the receiver Bob stores the received qubits in a quantum memory and measures them *after* the sender Alice tells him the bases), (ii) improving the EPR-based QKD schemes [1], (iii) teleporting a state using singlet pairs prepared in advance, (iv) new schemes for QKD that rely on the existence of short-term memory [2, 3], (v) attacking oblivious transfer and quantum bit commitment schemes [4], etc.

The requirements for quantum memory are thought to be very different from those of quantum gates. In a quantum gate, the qubits are accessed and rotated numerous times, but the coherence time need not be very long; it simply has to be much longer than the switching time. In contrast, the qubits in a quantum memory are seldom accessed, but they must live much longer (ideally “forever”) without decohering. One must also be able to access them with high fidelity.

2 Spintronic quantum memory

The most popular scalable solid state quantum gates are based on manipulating the spins of single electrons or holes in quantum dots [5, 6] or in single dopant atoms [7, 8]. For the sake of compatibility, we must implement quantum memory in the same systems¹.

Because of the relatively short coherence time of electron or hole spins, *non-volatile* quantum static memories (Q-SRAMs) are not appropriate; rather, quantum *dynamic memories* (Q-DRAMs) may be possible if the qubit can be *refreshed* periodically through refresh cycles. Below, we explore possible routes to refreshing the quantum state of a quanton.

2.1 Refreshing a qubit

It is very possible that refreshing can be accomplished through the *quantum Zeno effect* which postulates that repeated observations of a qubit will inhibit its decay [9, 11]. Repeated observations automatically serve as refresh cycles. However, this repeated observation has to be carried out by a non-invasive detector. A ballistic point contact has been used in the past as a non-invasive charge detector for electrons in quantum dots [10], and its role in the context of the quantum Zeno effect has been examined [11]. It may be possible to use a spin-polarized scanning tunneling microscope tip as a non-invasive probe for spin, but that is yet to be realized in practice.

A more straightforward approach would be to read the qubit periodically and then re-create *some* (but not all) attributes of it. Since, we are not going to use the memory for

¹The coherence times of electron or hole spins are much less than that of nuclear spins. However, nuclear spins are not easy to “read” as data; consequently, one must couple the nuclear spin to an electron spin and then detect the electron spin [7] to read the original nuclear spin. This transduction of a nuclear spin to an electron spin is a delicate process and difficult to implement with high enough fidelity.

computation (such as implementing Shor’s or Kitaev’s algorithms, or Grover’s sorter), we may not need to draw upon the full power of quantum parallelism. The expectations from “memory” are different from those that we expect from “logic gates”. We may not need the full phase information in many cases.

Consider the qubit encoded by the coherent superposition of two spin states of a quanton:

$$\begin{aligned} |\psi\rangle &= a_{\uparrow}|\uparrow\rangle + a_{\downarrow}|\downarrow\rangle \\ |a_{\uparrow}|^2 + |a_{\downarrow}|^2 &= 1 \end{aligned} \tag{1}$$

If we make several measurements of this qubit we will measure the upspin state with a probability $|a_{\uparrow}|^2$. Thus, by making several measurements over identical qubits, we can find the magnitudes of a_{\uparrow} and a_{\downarrow} , but not the relative phase between them. *In many applications involving measurements of stored qubits on given bases, it may be sufficient to know just the magnitudes of a_{\uparrow} and a_{\downarrow} , and the relative phase is unimportant.* For such niche applications, we can develop a Q-DRAM with present technology as explained below.

One can periodically read the qubits (with a period much smaller than the decoherence time) in several nominally identical hosts (e.g. single-electron quantum dots) to extract the magnitudes of a_{\uparrow} and a_{\downarrow} . After each reading, we will re-inject quantons into these dots from a spin polarized contact, followed by immediate single qubit rotations in every dot to re-create the magnitudes of a_{\uparrow} and a_{\downarrow} (but not the relative phase, which will be arbitrary). In this fashion, we can store the magnitudes of a_{\uparrow} and a_{\downarrow} for an indefinite time. This is a crude, but often effective, quantum dynamic random access memory (Q-DRAM).

2.2 Why quantum dots?

Single quantons confined in quantum dots are ideal storage media from the vantage point of technology. Large, well-ordered arrays of quantum dots can be self-assembled with a density exceeding $10^{11}/\text{cm}^2$. This can lead to unprecedented density of qubits – in excess of $10^{11}/\text{cm}^2$. Thus, even if we introduce a 100-fold redundancy (the same qubit is stored in 100 dots), we can still obtain a qubit storage density in excess of 1 giga-qubit in 1 cm^2 (smaller than a postage stamp) whose storage capacity of 2^{10^9} exceeds by far that of all the hard disks that could have been made with all the material in the universe over the life of the universe.

Fig. 1 shows a self assembled porous alumina film produced in our laboratory by anodization of aluminum [12]. The pores can be filled sequentially with different materials to create multi-layered quantum dots surrounded by alumina. Alternately, the pores can be used as etch masks to mesa-isolate quantum dots in a multilayered film grown by molecular beam epitaxy [13]. Using these techniques, one can grow semiconductor quantum dots capped by ferromagnetic contacts that act as spin polarizers for injecting spin, and spin analyzers for detecting spin.

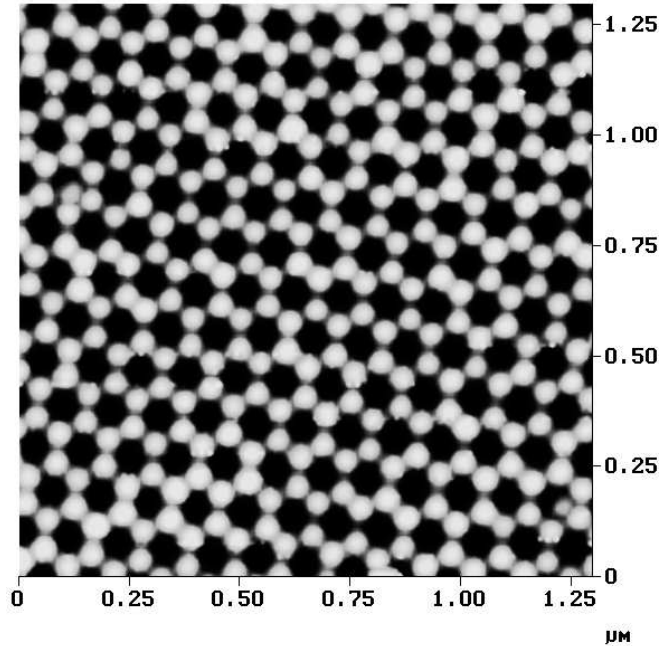


Figure 1: Raw atomic force micrograph of pore morphologies produced by anodization of an aluminum foil in oxalic acid. The average pore diameter is 52 nm with a 5% standard deviation. This structure acts as a self-assembled template for self-assembling a quantum memory.

3 Quantum erasure

Before concluding this paper, we point out that there is theoretically an intriguing possibility of actually re-creating the entire qubit (including the phase) after it has been “read”. i.e. after the spin analyzer has detected the spin orientation. This involves *quantum erasure* [14, 15, 16]. To implement quantum erasure, we need only one difficult technological feat. When the quanton passes through the spin analyzer, it should be able to rotate the magnetization of the analyzer and *change it*. In other words, the magnetization of the analyzer must be sensitive to the passage of a quanton and respond to it. At present, this is not possible; but the recent discovery of control of magnetization via an electric current in InMnAs [17] is beginning to hold out some hope in this direction.

Consider a quanton in a coherent superposition of two spin states, described by a wavefunction

$$\psi = a_{\uparrow}|\uparrow\rangle + a_{\downarrow}|\downarrow\rangle \quad (2)$$

A fundamental result of quantum measurement theory is that if the spin analyzer tries to detect the spin of the incoming quanton, the wavefunction of the detector becomes entangled with that of the quanton. The entangled (non-factorizable) wavefunction is

$$\Phi = a_{\uparrow}|\uparrow\rangle|1\rangle + a_{\downarrow}|\downarrow\rangle|2\rangle \quad (3)$$

where the wavefunctions $|1\rangle$ and $|2\rangle$ span the Hilbert space of the detector. Thus, $|1\rangle$ corresponds to the detector (spin-analyzer) passing an up-spin quanton, and $|2\rangle$ corresponds to the detector reflecting a downspin quanton.

If we make a measurement of whether the detector passed the quanton (corresponding to the determination that the quanton's spin was "up"), the probability amplitude of that is

$$\Psi = \langle 1 | \Phi \rangle = a_{\uparrow} | \uparrow \rangle \langle 1 | 1 \rangle + a_{\downarrow} | \downarrow \rangle \langle 1 | 2 \rangle \quad (4)$$

Since the detector makes an "unambiguous" determination, meaning that it *always* passes an upspin quanton and *never* passes a downspin quanton, the wavefunctions $|1\rangle$ and $|2\rangle$ are orthogonal, meaning that upspin detection and downspin detection are mutually exclusive (a quanton cannot be simultaneously both upspin and downspin, and the detector will unambiguously determine what the spin is). Hence, from Equation (3),

$$\Psi_{\text{detected}} = a_{\uparrow} | \uparrow \rangle; \quad |\Psi|^2 = |a_{\uparrow}|^2 \quad (5)$$

and we get no information about a_{\downarrow} , or the phase. This is interpreted as wavefunction collapse. However, this collapse is not irreversible since if we design an experiment whose result is the probability of a particular outcome of the spin measurement *and* finding the detector in the symmetric state ($|1\rangle + |2\rangle$), then the corresponding probability amplitude is

$$\begin{aligned} [\langle 1 | + \langle 2 |] | \Phi \rangle &= a_{\uparrow} | \uparrow \rangle \langle 1 | 1 \rangle + a_{\downarrow} | \downarrow \rangle \langle 1 | 2 \rangle + a_{\downarrow} | \downarrow \rangle \langle 2 | 2 \rangle + a_{\uparrow} | \uparrow \rangle \langle 2 | 1 \rangle \\ &= a_{\uparrow} | \uparrow \rangle + a_{\downarrow} | \downarrow \rangle \\ &= \psi, \end{aligned} \quad (6)$$

which is the original wavefunction. Hence, we have restored the original wavefunction.

Note that if we can find the detector in the symmetric state, we would not have known whether the quanton that passed through it was "up" or "down", and hence we would not have collapsed the wavefunction. Thus, by finding the detector in the symmetric state, we have erased the information about the spin and hence restored the original coherent superposition state. The quantum erasure is possible because the entangled wavefunction Φ is still a pure state and not a mixed state.

4 Conclusion

In this brief report, we have pointed out the possibilities of quantum-dot based quantum dynamic random access memory (Q-DRAM), and outlined three possible schemes to implement qubit refreshing. The advantage of quantum dot based memory is the exceedingly large storage density that is possible.

References

- [1] A. Ekert. *Phys. Rev. Lett.*, **67**, 661 (1991).
- [2] C. H. Bennet and S. J. Wiesner, *Phys. Rev. Lett.*, **69**, 2881 (1992)
- [3] L. Goldenberg and L. Vaidman, *Phys. Rev. Lett.*, **75**, 1239 (1995).
- [4] T. Mor, D.Sc. thesis, LANL e-print quant-ph/9900073.
- [5] G. Burkard, D. Loss and D. P. DiVincenzo, *Phys. Rev. B*, **59**, 2070 (1999).
- [6] S. Bandyopadhyay, *Phys. Rev. B*, **61**, 13813 (2000).
- [7] B. E. Kane [*Nature* (London)], **393**, 133-137 (1998).
- [8] R. Vrijen, et. al., *Phys. Rev. A*, **62** 12306 (2000).
- [9] B. Misra and E. C. G. Sudarshan, *J. Math. Phys.*, **18**, 756 (1977).
- [10] M. Field, et. al, *Phys. Rev. Lett.*, **70**, 1311 (1993).
- [11] S. A. Gurvitz, *Phys. Rev. B*, **56**, 15215 (1997).
- [12] S. Bandyopadhyay, et. al., *Nanotechnology*, Vol 7, 360 (1996); S. Bandyopadhyay and A. E. Miller, in *Handbook of Advanced Electronic and Photonic Materials and Devices*, Vol. 6 (Nanostructured Materials), Ed. H. S. Nalwa (Academic Press, New York, 2000), Chapter 1.
- [13] H. Masuda and M. Satoh, *Jpn. J. Appl. Phys.*, **35**, L126 (1996).
- [14] M. Hillery and M. O. Scully, in *Quantum Optics, Experimental Gravitation and Measurement Theory*, Eds. P. Meyestre and M. O. Scully (Plenum, New York, 1983), p. 65.
- [15] M. O. Scully, B. J. Englert and H. Walther, *Nature* (London), **351**, 111 (1991).
- [16] P. G. Kwiat, A. M. Steinberg and R. Y. Chiao, *Phys. Rev. A*, **49**, 61 (1994).
- [17] H. Ohno, et. al., *Nature* (London), **408**, 944 (2000).